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NASA/CR-97- 112612

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AIAA 97-1927

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28th AIAA Fluid Dynamics Conference
4th AIAA Shear Flow Control Conference
June 29 - July 2, 1997
Snowmass Village, CO

Study of the Unsteady Flow Features on a Stalled Wing

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Abstract

The occurrence of large scale structures in the post stall flow over a rectangular wing at high angles of attack was investigated in a small-scale subsonic wind tunnel. Mean and time dependent measurements within the separated flow field suggest the existence of two distinct angle of attack regimes beyond wing stall. The shallow stall regime occurs over a narrow range of incidence angles (2 - 3 deg.) immediately following the inception of leading edge separation. In this regime, the principal mean flow structures, termed stall cells, are manifested as a distinct spanwise periodicity in the chordwise extent of the separated region on the model surface with possible lateral mobility not previously reported. Within the stall cells and on the wing surface, large amplitude pressure fluctuations occur with a frequency much lower than anticipated for bluff body shedding, and with minimum effect in the far wake. In the deep stall regime, stall cells are not observed and the separated region near the model is relatively free of large amplitude pressure disturbances.

Introduction

The transition from an attached flow field over a wing into a time dependent, partially separated flow, is still not completely understood in spite of its importance to many disciplines where high lift is necessary. In addition to possible benefits from increasing the lift of wings beyond their stall angle, the understanding of such flows can lead to the reduction of airframe noise, delay structural failure due to fatigue and flutter, or even improve airplane safety in conditions such as stall/spin. Most experimental investigations with stalled wings (e.g. Ref. 1) document the time dependent nature of the separated flow, often with clearly structured vortex shedding patterns. However, even when a two dimensional approach is taken, the Karman type vortex shedding model with its unique frequency ($St \approx 0.15^{\#}$) is not the only pattern observed. In fact, a large body of evidence suggests that the fluctuations associated with stall flutter occur at much lower Strouhal numbers, in the range $0.02<St<0.05$ (See Ref. 1,2, and 3). Zaman et al.[4], in their two-dimensional investigation, found these low frequency fluctuations to occur within a narrow range of incidence angles beginning just after the onset of separation, near the point of maximum lift. Zaman et al.[4] and earlier, Moss[5], both suggest that the low frequency phenomena are related to a periodic stall/unstall mechanism. During three-dimensional flow visualization experiments with high-aspect ratio wings, past the point of stall, a periodic spanwise cellular pattern was observed[6,7], with narrow attached flow regions between the separated cells. The regions of separated flow, termed stall cells, appear along the wing span with the number of cells determined by aspect ratio. Initial efforts to explain the periodicity of those stall cells led Weihs & Katz[8] to formulate a model for stall cell formation based on a Crow[9] type instability of spanwise vortices formed by the separated leading edge shear layer.

When combining the experimental information gathered by the two and three dimensional experiments, several questions arise, particularly regarding the relation between the periodic wake shedding and the spanwise cellular patterns. Also, how and if the two fundamental frequencies relate to each other, and what effect the resulting flow structures have on the pressure fluctuations on the wing surface and on the lift. The objective of the present study, therefore, is to provide additional information on the three-dimensional, time dependent flow near the stalled wing and in its wake in terms of flow visualization and pressure measurements so that some of the above questions may be addressed.

Method of Investigation

The wind tunnel used in the current experiment is a subsonic, closed circuit, vertical return facility with a 32" x 45" atmospheric pressure test section, with turbulence levels on the order of 1% (in the test section). The experiments focused on generating the aerodynamic loads, surface pressures, their time-dependent fluctuations, and on surface flow visualizations. A schematic description of the wing, as mounted in the wind tunnel is shown in Fig. 1a. The wing model employed in the experiment consists of six spanwise segments, each of unit aspect ratio and 6 in. chord. A photograph of one segment is shown in Figure 1b. These segments may be combined to form a constant chord unswept wing with aspect ratio (AR) variable in integer increments from AR=2 to AR=6. Each segment incorporates the NACA 0015 symmetric airfoil section to facilitate investigation of upper/lower surface phenomena. The addition of 11 in. square tip plates allows the development of upper surface flow features with reduced influence from tip vortices (one tip plate is shown in Fig. 1a). Model incidence angle is variable between 0

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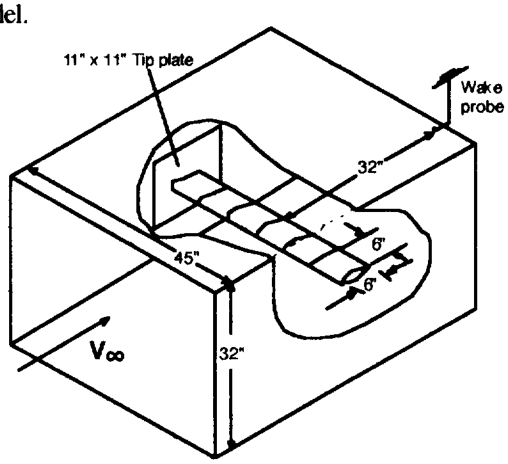
# Note that the Strouhal number is defined here: $St=\omega l/V$, where l is the frontal projected height (e.g. c $\sin\alpha$).

and $\pm 28°$, and maximum blockage (at maximum incidence) is approximately 7%. All the results presented in this paper correspond to a Reynolds number of 620,000 (at a free-stream speed of 140 mph). One surface of each of the model segments is tufted for flow visualization (as shown in Fig. 1b). Tuft orientations are photographed through the clear roof of the test section to provide a record of the surface flow averaged over the length of the exposure. Time dependent behavior of the tufts is recorded on VHS tape with an oblique view down the span of the model.

a



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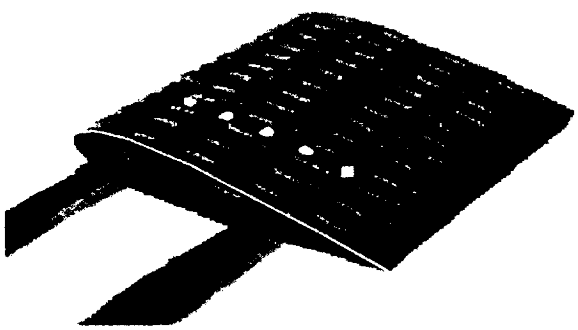

Fig. 1 Layout of the rectangular wing in the wind-tunnel test section (a), and the instrumented model segment showing surface tufts and pressure transducers (b). The wiring and static pressure tubes are contained entirely within the model and exit through the tip.

One of the model segments is instrumented for mean and high frequency static pressure measurements. Five static pressure ports and five Endevco piezo-resistive static pressure transducers are arranged in a chordwise array approximately 1 1/2 in. from the edge of the model segment as shown in Figure 1b (see 5 small circles). The transducers respond to absolute pressure from 0 to 15 psi with a resolution of 0.00025 psi, and a maximum frequency response greater than 150,000 Hz. The small size of the active area (<0.01 sq. in.) allows examination of relatively fine scale structure in the unsteady pressure field. The pressure field characteristic of various regions of the separated flow (e.g. within the separation cells) is obtained by moving the instrumented segment to the appropriate spanwise location on the model. A single transducer mounted on a vertical streamlined strut 32 in. downstream of the trailing edge serves as a wake pressure probe (see Fig. 1a).

Each of the five pressure transducers is DC coupled to a signal conditioner through doubly shielded wires to minimize static noise and crosstalk. Typical signal to noise ratios are on the order of 100-1000, and the minimum pressure fluctuation which can be resolved is of the order of the noise in the signal (approx. 0.00025 psi). Transducer output voltages are acquired with a timed sweep through the transducer array resulting in a Nyquist frequency of 7.5 kHz in each channel. The resulting data set contains six sequences of digitally sampled transducer output voltage data, each consisting of 4400 samples spanning 0.293 seconds. While the sweep rate employed in this experiment is substantially higher than the frequency of any anticipated natural pressure fluctuation, it is necessary for the resolution of any distinct waveforms in the pressure histories. Application of fourier transform (FFT), auto correlation, and cross correlation algorithms were used for the analysis of the resulting pressure histories in time and frequency space. A complete description of the data reduction procedures is given in Yon[10].

Flow Visualization, Average Pressures, and Loads

The mean surface features associated with the separated flowfield are visualized with an array of fine tufts on the upper surface of the model. These tufts are free to respond to transient flowfield events and thus may also give some indication of the unsteady characteristics of the flow. During the experiment, the model angle of attack was increased until the onset of stall and the cellular separation patterns formed. The stall cell phenomenon is observed in the present results in a narrow angle of attack range, spanning 2 or 3 degrees at most, beginning around 17 degrees angle of attack. A typical two cell pattern observed in the present experiment is shown in Figure 2a, which is an enhanced photograph of the upper surface of an AR 6 model at 17 degrees. Below, a schematic of the key features of the surface flowfield are presented. Each cell is defined by the line of separation which displays the characteristic 'owl's eye' pattern reported by Winkelmann & Barlow[7]. Within the stall cells, rapid movements of the tufts indicate a largely unsteady environment, while outside of the cells, very little tuft motion is noted. The region of attached flow between adjacent cells extends to the mid-chord, while downstream of this point, tuft motion indicates increased unsteadiness and possibly separation near the trailing edge.

The mean direction of the surface flow adjacent to the cell boundaries is indicated by the arrows in Figure 2b. The circulation around the lateral cell boundaries, implied by the variation of the surface velocity within and external to the individual cells, is consistent with the presence of spiral nodes terminating the line of separation on the wing surface, as noted by Winkelmann & Barlow[7]; although these nodes are not directly observed in the present results. The direction of the near surface flow in and around the separation cells has implications for the orientation of the vorticity vector in the separated shear layer. Near the centerline of each cell, where the spanwise velocity component is absent, the vorticity vector on the model surface (along the line of separation) must point in the spanwise direction. On either side of the centerline of the cell, however, in association with the spanwise velocity components near the model surface, the vorticity vector must have a significant streamwise component. The sense of the streamwise vorticity in the shear layer on either side of the cell is consistent with the circulation around the spiral nodes inferred to exist at the lateral boundaries of the line of separation (i.e. both lateral edges induce an 'upward' velocity component at the centerline of the cell). The lateral edges of each shear layer may therefore be bounded by a zone of streamwise vorticity which 'rolls up' into vortex cores which join the wing surface at the location of the spiral nodes. Winkelmann & Barlow[7] suggest that these vortices are connected across the cell in a coherent spanwise vortex. The actual location of the vortex cores away from the model surface is not indicated by the surface flow visualization, but may be inferred from the mean surface pressure distribution, to be discussed subsequently.

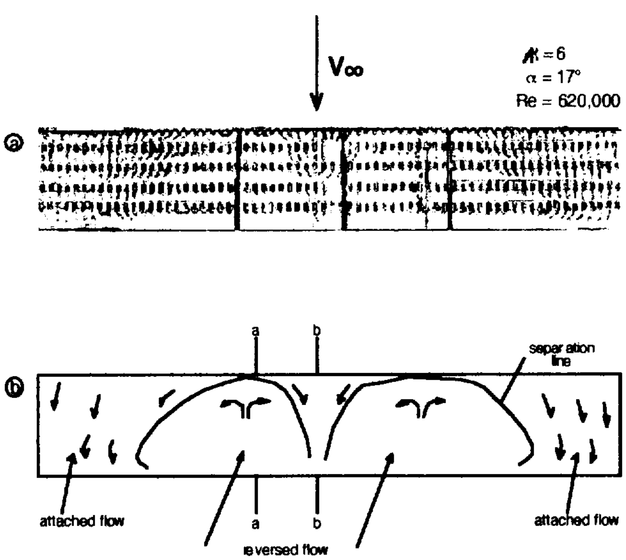

Fig. 2 Enhanced photograph of tuft orientations showing a stable two cell separation pattern on the aspect ratio 6 model (a) and a schematic outline indicating the approximate location of the line of separation (cell boundary) (b). Sections a-a and b-b mark the locations of the transducer and static pressure arrays, relative to the stall cell boundaries, during data acquisition.

When more than one cell is observed on the wing surface, (e.g. the two cell pattern shown in Figure 2), each cell exhibits an irregular dynamic motion best described as 'jostling'. Slight lateral movements of any cell result in a corresponding adjustment in the adjacent cells. These movements seem to be arbitrary, and may be slight or vigorous, and in the latter case one of the cells may momentarily merge with another. The unsteady nature of the separation cells becomes apparent only through the use of visualization techniques which respond on time scales of the order of the unsteady motions (e.g. small surface tufts). The surface oil technique employed by Gregory et al.[6] and Winkelmann & Barlow[7] has a relatively long response time, so that this motion had not been previously reported. A distinct frequency for the lateral motion of the cells was not observed.

The number of discrete cells observed in the separated flowfield above the incipiently stalled wing depends on the wing aspect ratio, as noted by Winkelmann & Barlow[7], and the dependence is summarized in Figure 3. The tip plates employed in the present experiment allow the formation of a larger number of cells on a model of fixed aspect ratio, and the net effect is seen to be a displacement

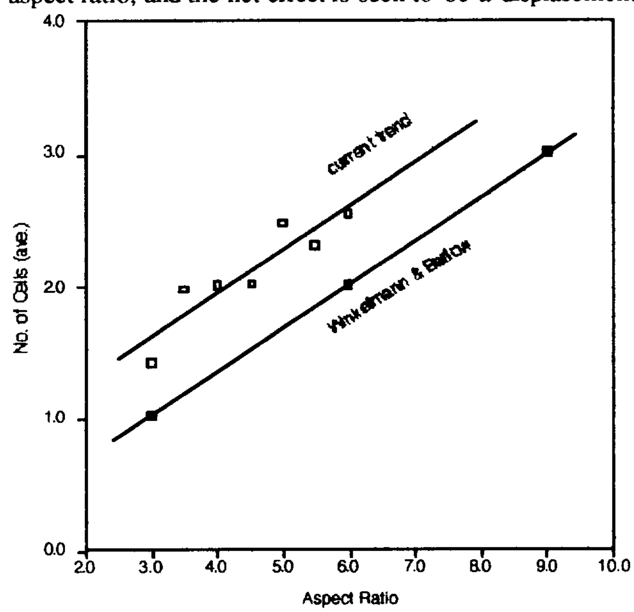

Fig. 3 Number of observed cells as a function of wing aspect ratio obtained with tip plates (open symbols) and without tip plates (closed symbols, from Winkelmann and Barlow, 1980). Non-integer numbers of cells indicate unstable switching between two integer cell patterns (e.g. 2.5 cells indicates switching between 2 and 3 cell patterns with equal amounts of time in each pattern).

in the ordinate of the best fit line from the experimental data of Winkelmann & Barlow[7]. In both cases, each stable cell is seen to occupy a region approximately two chords in width. The lateral extent of a cell is essentially independent of the number of cells observed and appears to be controlled by a chordwise length scale. Models exhibiting one, two or three cell patterns all produce cells of approximately the same width.

The stability of a given separation pattern (no. of cells) on a model of fixed aspect ratio is defined by the relative amount of time over which that pattern is observed. A stable pattern is therefore one which is observed almost exclusively. Unstable patterns result when the model aspect ratio is intermediate between two values for which stable patterns are observed. In Figure 3, models of aspect ratio between 3.5 and 4.5 produce 2 cell patterns which are stable. Increasing the aspect ratio to 5.0 - 6.0 results in an unstable switching between 2 and 3 cell patterns. The essential difference between a stable pattern and an unstable pattern appears to be the width of the attached region between adjacent cells. If this region is either too wide or too narrow (the preferred width seems to be of the order of half the cell width) then adjustment occurs by the formation or destruction of a cell.

Surface pressure measurements within the partially separated flow consisted of separate time average and time dependent recordings. The mean static pressure within the separation cells (section a-a in Fig. 2b) and in the intervening attached regions (section b-b in Fig. 2b) is shown in Figure 4. For comparison, the ideal (attached) flow solution for the same geometry (indicated by the solid line) is computed with a three dimensional potential-flow code (e.g. see Ref. 11, Ch. 11). Within the separation cells (Fig. 4a), the mean static pressure is essentially constant, and the separated flow extends to the region of the leading edge, in agreement with the flow visualization. Mean pressure on the lower surface of the model is very close to the potential flow prediction. In the medial attached regions (Fig. 4b), mean static pressure on the upper surface deviates from the potential prediction over the entire section, but appears to be consistent with an attached flow at a reduced angle of attack over the forward half of the section. The dashed lines represent the potential solution at 10 deg. angle of attack to illustrate this downwash effect of the stall cell vortices. Away from the wing tips, the source of the downwash resulting in this reduced angle of attack is not immediately apparent. Toward the trailing edge, the pressure in the medial attached region on the upper surface is essentially constant, which is consistent with separated flow and in agreement with the flow visualization.

Previous investigators[7] have postulated the existence of a coherent spanwise vortex core spanning each stall cell and connecting the spiral nodes which terminate the line of separation bounding the cell. The net effect of a spanwise vortex would be an induced upwash across the entire span of the model, which is not consistent with the increased downwash in the medial attached regions suggested by the mean pressure distribution, as shown in Figure 4. If, instead, the vortices which join the model surface at the location of the spiral nodes trail downstream, then the net effect would be an induced upwash within the cell, and a downwash in the medial attached regions which would then 'see' an effectively smaller angle of attack. To summarize the results of the flow visualization, a schematic description of the observed mean flowfield is shown in Figure 5. In addition to consistency with the observed pressure distribution, this model is consistent with the cell motion and stability observed in the present experiment. If the size of the cells is fixed (through some other mechanism) then increasing the aspect ratio from that resulting in a stable separation cell pattern will result in increasing the size of the medial attached regions, which remain attached because of the downwash induced by the adjacent cells. At some critical aspect ratio, the downwash induced on the expanded medial attached regions will no longer be sufficient and another separation cell will form. Alternately, if the aspect ratio is reduced, the cells are forced together and one will eventually be destroyed by the induced downwash from its nearest neighbors. Similarly, random lateral motions of a cell will result in changing the distribution of induced downwash which forces a corresponding adjustment of the positions of the remaining cells.

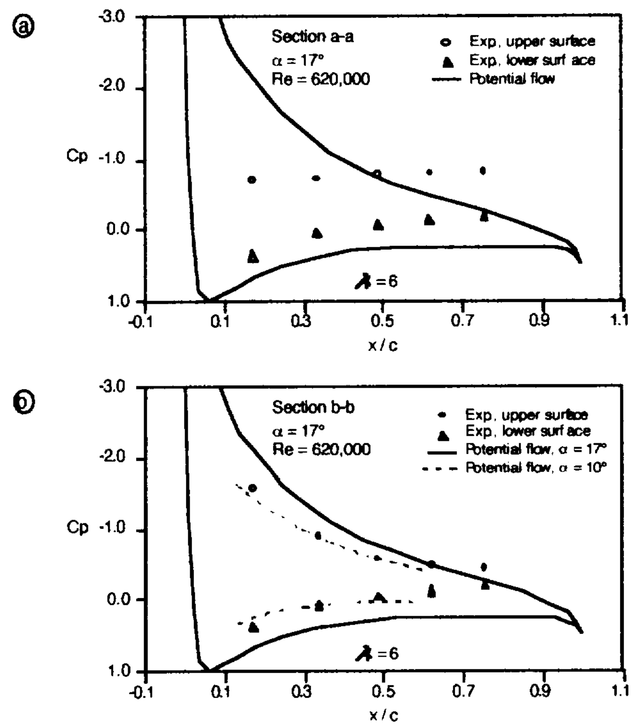

Fig. 4 (a) Mean static pressure recorded within a separation cell, corresponding to section a-a in Figure 2. The solid line is the three dimensional potential solution. (b) Mean static pressure recorded in the attached region between two cells, corresponding to section b-b in Figure 2. The solid line is the three dimensional potential solution at 17 deg angle of attack, and the dashed line is the potential solution at a reduced angle of attack (10 deg).

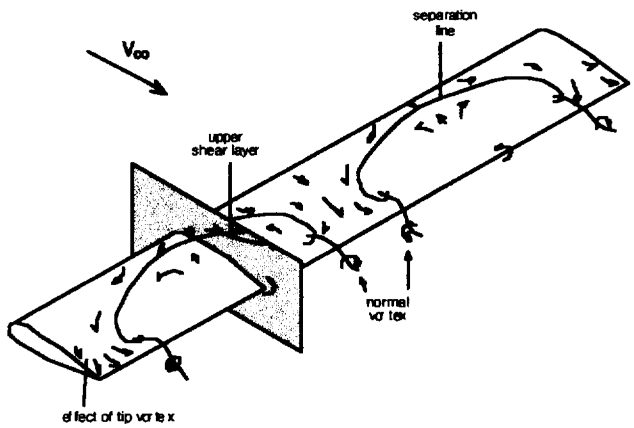

Fig. 5 Schematic model for the observed mean flow field associated with the cellular separation. The shear layers originating on the line of separation are bounded by normal vortex cores which trail downstream. Trailing edge vorticity and wing tip vortices have been neglected for clarity.

The effect of the stall cell separation on model lift can be deduced from the experimental data shown in Figure 6, for an aspect ratio 6 model which experiences stable 2 cell separation. The data points represent a typical α-sweep, with increasing and decreasing angles of attack. The finite lift at zero incidence is attributed to an error of approximately 1 deg. in the angle of attack calibration. The hysteresis in the range where the stall cells appear ($\alpha = 17^0$-19^0) is marginal. The cellular separation pattern develops a few degrees after the point of maximum lift (C_{Lmax}) and the onset of separation at the trailing edge.

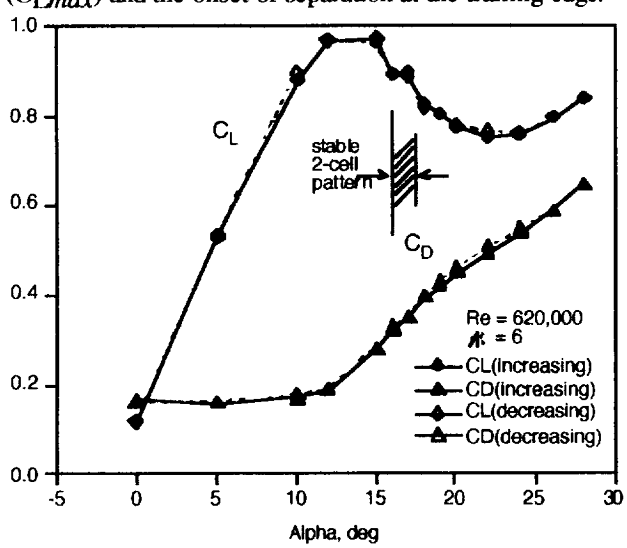

Fig. 6 Variation of mean lift and drag coefficients with increasing and decreasing angle of attack, for the aspect ratio 6 model.

This condition is reflected in a minor reduction in the rate of lift loss with increasing angle of attack in addition to a reduction in the variance of the measured lift coefficient compared to that measured at higher and lower incidence angles. The qualitative effects of the separation cells on the drag coefficient are similar but are slightly smaller in magnitude. The result is that while no significant gains in lift/drag ratio are realized at the optimal separation cell incidence angle, the effect of the developing separation pattern is to reduce the severity of stall by broadening the angle of attack range over which the stall occurs.

Unsteady Pressure

Time dependent static pressure measurements are obtained by positioning the instrumented model segment such that the transducer and static tap arrays sample the desired region of the separated flowfield. For brevity, most of the pressure data presented here correspond to the AR 3 model. Similar data from higher AR models can be found in Ref. 10. Pressure histories typical of those observed near the trailing edge (upper surface) are shown in the inset to Figure 7. The α = 10 deg. trace was obtained in an attached flow condition and serves as a reference signal, while the remaining two were obtained in the separated region near the center of the AR 3 model. Note that the largest fluctuations occur at the beginning of the range over which stall cells are observed (i.e. 17 to 19 deg.), and that relatively small changes in model incidence can result in large changes in the character of the signal. Analysis of the separated flow pressure histories indicates that low frequency (St < 0.15) fluctuations similar to those reported by Zaman et al.[4] occur in the separated region in association with the stall cells described in the previous section.

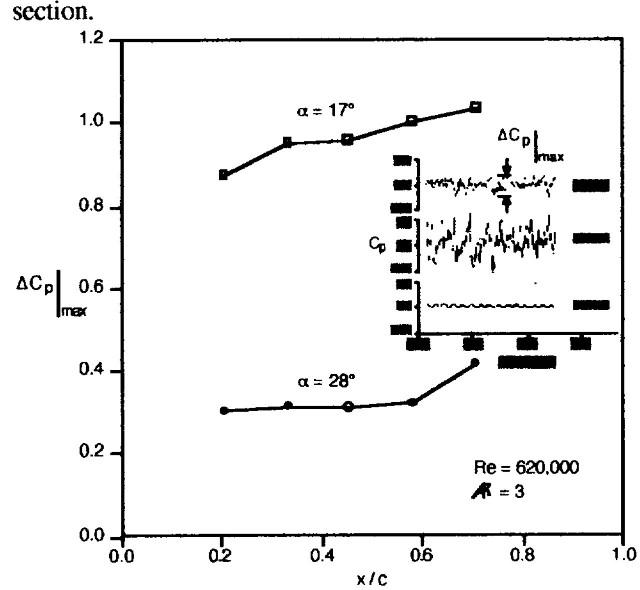

Fig. 7 Maximum amplitude of static pressure fluctuations within a stall cell at 17 deg (upper), and in the separated region at 28 deg angle of attack (lower).

The amplitude and frequency content of pressure fluctuations recorded within the separated region on a model which exhibits cellular separation are summarized in Figures 7 and 8 respectively. The amplitude of the fluctuating pressure is defined in the inset to Figure 7. The largest pressure fluctuations, represented by the upper series of points in Figure 7, exhibit significant streamwise growth along the wing section and occur in association with separation cells at 17 deg. angle of attack. These fluctuations occur in two distinct frequency ranges (labeled 'fan triggered' and 'natural' in Figure 8), both of which correspond to Strouhal numbers less than that associated with bluff body shedding (St < 0.15). Outside of the narrow range of incidence angles associated with cellular separation, the amplitude of the measured surface pressure fluctuations is much less, and the low frequency signal is absent. These observations suggest division of the range of orientations examined into two regimes; shallow stall (where cellular separation is observed), and deep stall, each of which is discussed in detail below.

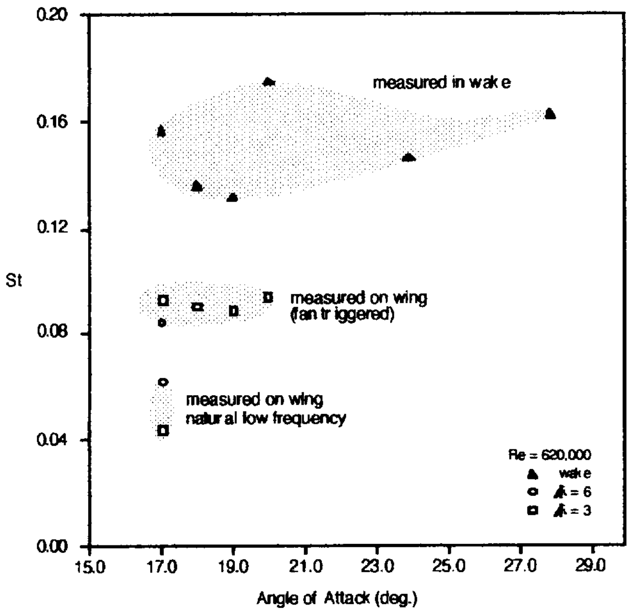

Fig. 8 Variation of the Strouhal number associated with pressure fluctuations in the wake and on the model surface as a function of angle of attack.

The shallow stall regime is characterized by the appearance, 2 or 3 degrees after the first indications of separation at the trailing edge of the model, of separation cells in the upper surface flow field and large amplitude, low frequency static pressure fluctuations within the separated flow on the model surface. Examples of pressure histories from all five surface pressure transducers, recorded near the centerline of a separation cell at 17 deg. angle of attack, are shown together in Figure 9, in which the pressure histories are presented sequentially from the leading edge, with the leading edge record at the bottom of the figure. Over the duration of the pressure data acquisition, the fluctuations appear to be stationary. The largest pressure fluctuations occur in the records from all 5 transducers and generally exhibit significant streamwise growth. The pressure fluctuations characteristic of the shallow stall regime occur, with decreasing amplitude at higher incidence angles, up to 19 or 20 deg. angle of attack.

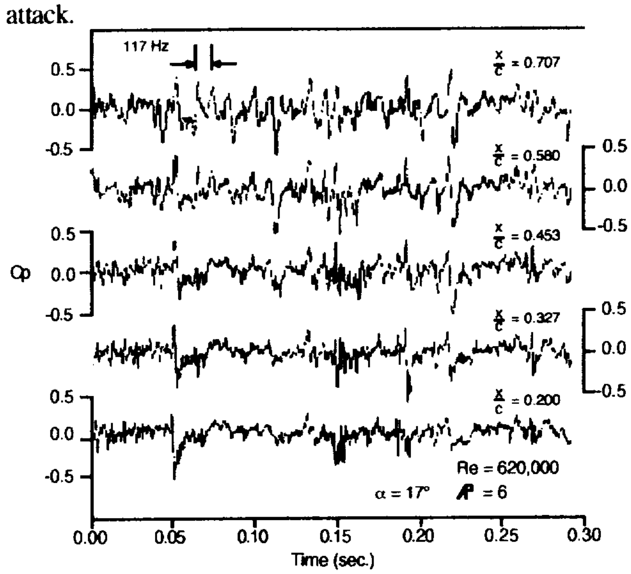

Fig. 9 Time histories of pressure coefficient associated with forced low frequency fluctuations within a stall cell. These are to be viewed as fluctuations around the mean of each signal. The transducers are numbered sequentially from the leading edge (lowest), and the chordwise location of each transducer is indicated to the right. The period of the 117 Hz component is indicated in the topmost trace.

The frequency space representations of the stall cell pressure histories are shown in Figure 10. The power spectral density (PSD) estimators in Figure 10 are presented sequentially from the leading edge, with the leading edge at the bottom. The significant low frequency power (<50 Hz) is attributable to tunnel vibration (near the fan rotational frequency) and is not considered. The greatest streamwise growth in any frequency range occurs around 117 Hz, which is the blade pass frequency of the fan drive. Peak power occurs at this frequency in the record from the trailing edge transducer, and the streamwise growth of the large pressure fluctuations recorded during stall cell separation is attributed to increased power near this frequency. The strong 117 Hz fluctuations in the pressure histories recorded within the separation cells occur at a Strouhal number of approximately 0.08 - 0.10, represented by the shaded region labeled 'fan triggered' in Figure 8. Note that while this range is significantly lower than the value expected for vortex shedding from a bluff body (~0.15), it is still higher than the value of ~0.02 obtained by Zaman et al.[4]

A distinct waveform corresponding to the 117 Hz periodicity identified in the pressure histories recorded within the separation cells is shown in Figure 11. The waveform is characterized by a period of gradually increasing pressure followed by a more rapid reduction in pressure and is readily apparent only in the record from the trailing edge transducer, even though significant power at this frequency occurs over much of the section chord.

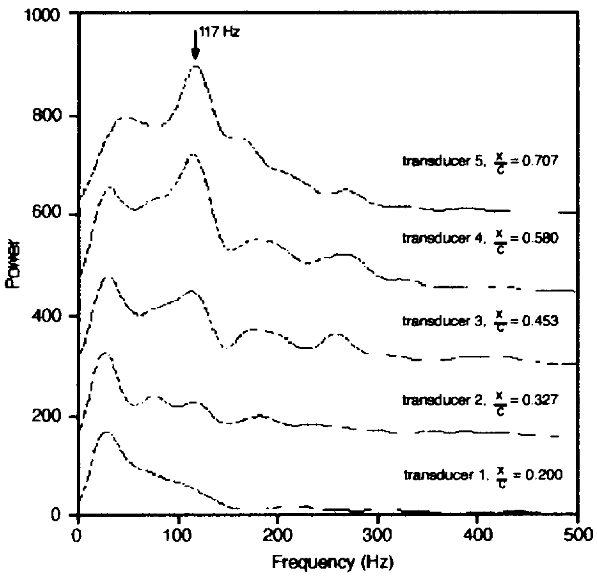

Fig. 10 PSD estimators computed from the time histories in Figure 9. The chordwise location of each transducer is indicated to the right. Successive spectra are vertically offset by 150 units for clarity. Power associated with strong 117 Hz component is indicated by the arrow at the top.

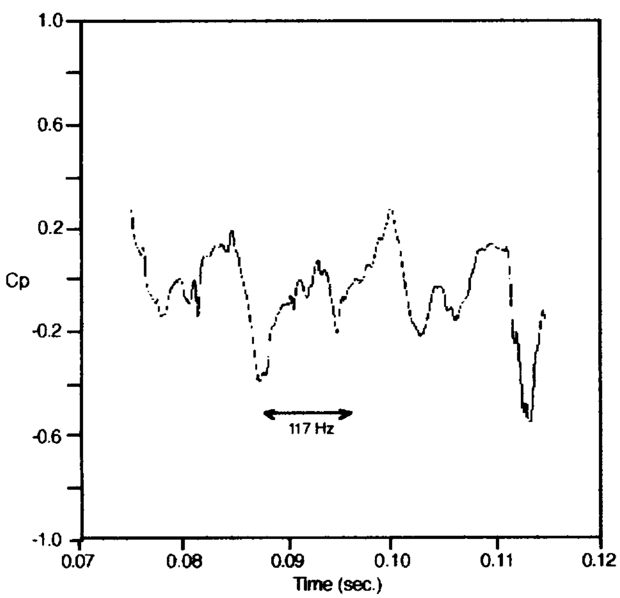

Fig. 11 Waveform associated with the forced 117 Hz pressure fluctuations. The period is indicated for reference. This waveform is clearly visible only in the records from the aft most transducer (x/c = 0.707).

Crosscorrelations of the leading edge pressure record in Figure 9 with the downstream pressure histories are shown in Figure 12. The transducers involved in each case are indicated above the corresponding curve. Crosscorrelation between any two adjacent transducers in the stall cell pressure histories results in peak coefficients greater than 0.7 and convective speeds, based on the delay to peak correlation and the streamwise separation of the transducers, of approximately half the freestream speed. While the peak correlation coefficient decreases with increasing distance between the two transducers, the computed convective speed is always close to half the free stream.

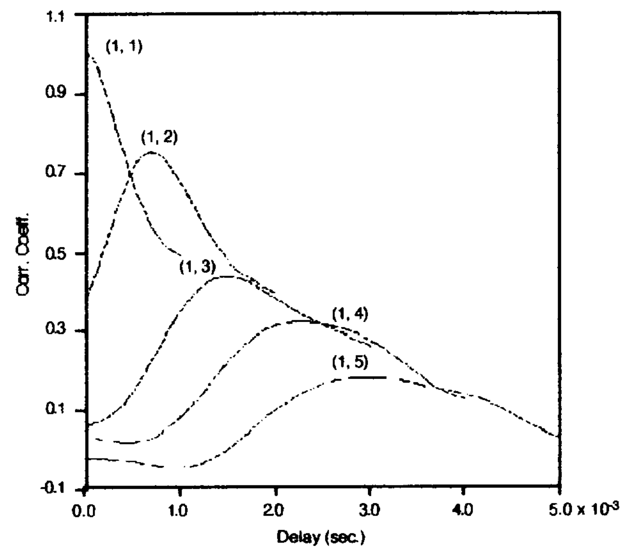

Fig. 12 Correlation coefficients between pairs of pressure histories in Figure 9, with the transducer pairs indicated in parentheses.

Length scales computed from the autocorrelation of each pressure record in Figure 9 are of the order of the size of the transducer array (3 in.), which suggests that the leading edge shear layer did not 'roll up' into a discrete spanwise vortex core in the vicinity of the model.

The pressure histories shown in Figure 9 are representative of one of two types containing large amplitude low frequency fluctuations which are observed within the separation cells. Both types exhibit significant streamwise growth of the lower frequency components and convection with approximately half the free stream speed, while the two types differ primarily in the frequency associated with the largest amplitude fluctuations. Peak power in the most commonly observed type, represented by the pressure histories in Figure 9, occurs near 117 Hz, the blade pass frequency of the fan drive. In the remaining type, which is much less frequently observed and occurs in a much narrower range of incidence angles, peak power occurs in a lower frequency range (near 75 Hz), corresponding to Strouhal numbers represented by the shaded region labeled 'natural' in Figure 8. This range of Strouhal numbers (~0.04) is much closer to the value obtained by Zaman et al.[4]. Previous studies[12] have shown that wake instabilities are susceptible to forcing at frequencies higher than the naturally occurring. In the present study, the ambient power in the test section (i.e. at the blade pass frequency of the fan drive) serves as the forcing function. The similarity of the essential features of the two types of fluctuations observed in the present study and the relative frequency of observation are consistent with the identification of the two as the natural and forced forms of the same phenomenon. The higher frequency (~117 Hz) more commonly observed fluctuations are therefore postulated to result from forcing the lower frequency (~75 Hz) natural fluctuations.

Stack et al.[13] reported a reversal in the phase of surface shear stress fluctuations across the line of separation on a lifting airfoil. A similar reversal in the phase of pressure fluctuations is noted in the present results when the visualized line of separation passes through the transducer array. This phase reversal is not observed in the stall cell pressure histories exhibiting the low Strouhal number fluctuations, which suggests that the line of separation does not exhibit significant streamwise movement and precludes the existence of the periodic stall/unstall mechanism postulated by Moss[5] as the source of the fluctuations in the present experiment.

In addition to the natural and forced fluctuations described above, a third type of pressure history is also observed within the stall cells. Over significant time intervals (>0.3 sec.) the pressure fluctuations within the cells may be quite small and without substantial power in either of the frequency ranges associated with the large amplitude signals described above. These periods of quiet separation suggest that the large amplitude, low frequency fluctuations are not causally related to the cellular separation patterns since the mean features of the flowfield (i.e., the stall cells) are independent of the type of pressure fluctuations recorded on the model surface.

Increasing the model angle of attack substantially beyond the optimal separation cell orientation results in loss of the cellular separation, loss of the large amplitude, low frequency fluctuations observed within the separation cells, and reduced amplitude of all pressure fluctuations within the separated region. Samples of pressure histories representative of this deep stall regime are shown in Figure 13. Comparison with the lower curve in Figure 9, which shows the streamwise variation of the amplitude of pressure fluctuations in this orientation, indicates that very little streamwise growth of the remaining fluctuations occurs. PSD estimators computed from the deep stall pressure histories are essentially featureless over the frequency range characterized by maximum streamwise growth and large power in the shallow stall data and bear an increased resemblance to the ambient signature of the test section environment, represented by the $\alpha = 10°$ trace in the inset to Figure 7.

Wake pressure fluctuations recorded in the shallow and deep stall regimes are shown in Figure 14, and the corresponding PSD estimators are shown in Figure 15. While the amplitude of the pressure fluctuations recorded

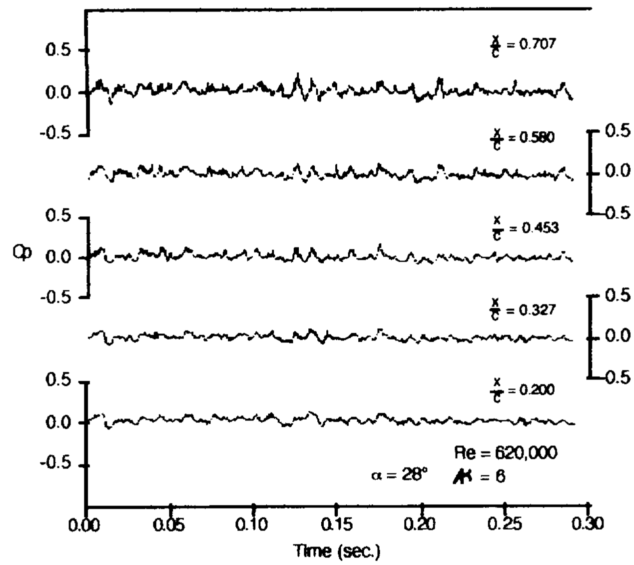

Fig. 13 Time histories of pressure coefficient recorded within the separated region at 28 deg. angle of attack.

by the wing mounted transducers is a strong function of model angle of attack, the amplitude of pressure fluctuations within the wake is less variable. Between 17 and 28 deg., the magnitude of pressure fluctuations encountered in the wake is nearly constant, but the dominant frequencies are not. Near the optimal separation cell angle of attack (~17 deg.), the PSD estimators obtained from the wake fluctuations contain peaks corresponding to both the forced frequency identified within the separation cells on the model surface (~117 Hz and labeled 'f' in Figure 15) and a higher frequency (labeled 'w' in Figure 15). Power at the forced frequency is

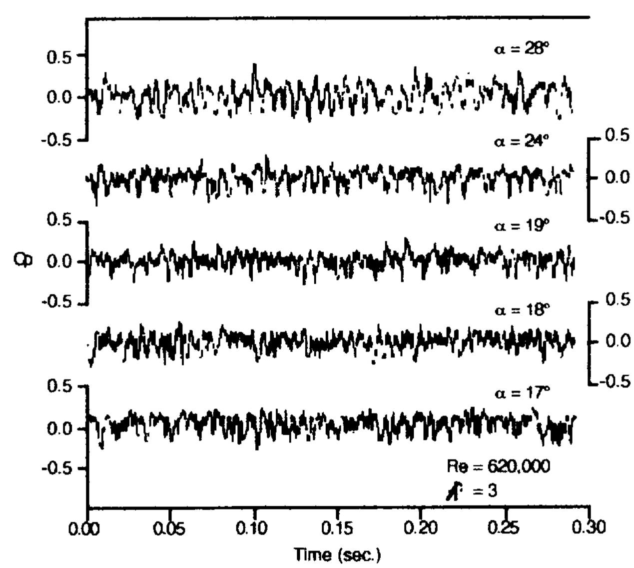

Fig. 14 Wake pressure fluctuations recorded 32 in. downstream of the trailing edge. The 17 and 18 deg. data were recorded at the spanwise location of the center of a stall cell.

significantly reduced from that noted in the model surface pressure histories. At higher angles of attack, the forced frequency vanishes while the remaining peak (w) occurs at reduced frequencies. Comparison with Figure 8 shows that this wake frequency occurs with a Strouhal number, St ~ 0.15, corresponding to the expected bluff body vortex shedding frequency at all model orientations. While power at the forced frequency may result from convection and decay of the structures responsible for the large amplitude fluctuations in the vicinity of the model, power at the higher frequency (w) was not noted in the PSD estimators from the surface pressure data and must result from formation of coherent structures in the evolving wake. Since the wake frequency is higher than the dominant model surface frequency, vortex pairing in the wake does not explain the observed behavior. Cimbala[14] has reported similar wake structures resulting from instability in the evolving wake profile downstream of a decaying von Karman vortex street.

The streamwise growth of the low frequency fluctuations observed in the shallow stall regime on the upper surface of the model, combined with the measured convective speed approximately equal to half the free stream speed suggest that the large amplitude fluctuations in the vicinity of the model are related to a convective instability in the leading and trailing edge shear layers bounding the separation cells. Over the model transducer array, the length scale associated with the largest pressure fluctuations is larger than would be expected from convecting coherent vortex cores close to the model surface, so that the surface pressure fluctuations within the separation cells are not simply the reflection of a reduced frequency von Karman vortex street in the vicinity of the model. Zaman et al.[4] observed a violent motion of the leading edge shear layer termed 'shear layer flapping', in association with the low frequency fluctuations. A convecting instability of the leading edge shear layer might be described as 'flapping', particularly if the line of separation were fixed near the leading edge, as noted in the present results. Although the flow visualization of Zaman et al.[4] is inconclusive, the 'flapping' shear layer does not appear to deform into discrete spanwise vortex structures, consistent with the results of the present study.

Zaman et al.[4] concluded that the low frequency fluctuations connected with the observed shear layer motions resulted from a turbulent or transitional state of the separated shear layer. While the state of the shear layer in the present experiment is unknown, the relatively high ambient turbulence in the test section combined with the rough surface of the model (due to the presence of the tuft strips) is consistent with this conclusion.

The apparent absence of concentrated spanwise vortex structures from the unsteady separated flow within separation cells, and the lack of an obvious cause/effect relationship between the cells and the low frequency pressure fluctuations, which are connected with large amplitude shear layer motions noted in previous efforts and inferred in the present study, leaves the source of the cellular separation patterns in question. There are several indications that cellular separation, while independent of the low frequency phenomenon, is also connected with a turbulent or transitional state of the separated shear layer. First, low Reynolds number (<15,000) water tunnel visualization[15] using an AR 3 half span model of a rectangular planform wing with the NACA 0015 section showed no evidence of separation cells regardless of angle of attack. Second, three dimensional numerical simulation[10] of the water tunnel experiments, assuming laminar flow, also failed to reproduce the separation cells. Very recently, a three dimensional numerical simulation[16] was performed using the same wing geometry at a much higher Reynolds number (>1,000,000) and including turbulent kinetic energy production. Preliminary results indicate that the characteristic multiple separation cell pattern can be reproduced numerically on rectangular wings of sufficiently high aspect ratio if turbulent conditions are assumed. In addition, the calculations to date have been steady state, supporting the observation that unsteady shear layer phenomena are not required for stall cell formation.

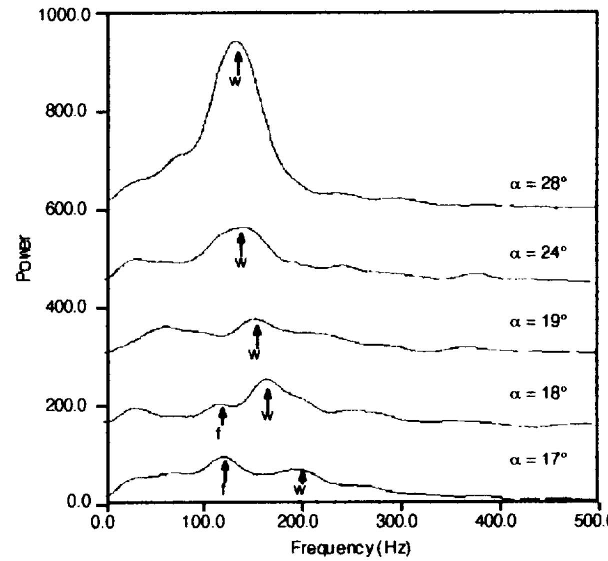

Fig. 15 PSD estimators computed from the wake pressure histories in Figure 14 (successive spectra offset vertically by 150 units on Power axis). 'f' indicates the frequency associated with the forced fluctuations in the vicinity of the model. 'w' indicates power associated with von Karman wake fluctuations.

The far wake, as determined by measurement of pressure fluctuations approximately 6 chords downstream of the model, is subject to an instability consistent with a von Karman vortex street in both the shallow and deep stall regimes, independent of the state of the separated region in the vicinity of the model. While the large amplitude low frequency fluctuations recorded on the model surface in the shallow stall regime may persist some distance into the wake, the structures responsible for the pressure fluctuations recorded in the near and far wake regions are essentially independent at all model incidence angles.

The low frequency fluctuations recorded on the model surface, which may correspond to the shear layer flapping noted by Zaman et al.[4], occur within a restricted range of incidence angles and appear to result from a fundamental instability of the (turbulent) separated flow, distinct from the von Karman vortex street, which is subject to forcing at externally imposed frequencies.

Conclusions

Spanwise cellular patterns in the post-stall flow over rectangular wings have been observed in association with large amplitude surface pressure fluctuations which occur with frequencies much lower than those anticipated for bluff body shedding. Analysis of the unsteady pressure histories suggests that while both phenomena may be related to instabilities in the separated shear layer, there is no simple connection between the two. While the separated leading edge shear layer appears to convect downstream without deforming into discrete spanwise vortices in the vicinity of the model, accumulation of lower surface vorticity, resulting in periodic shedding of vortices from the trailing edge of the wing, may be responsible for the low frequency fluctuations. In addition, the apparent lack of discrete structures resulting from deformation of the separated shear layer precludes subsequent deformation of these spanwise vortices as the cause of cellular separation. In the wake, instability of the evolving wake profile results in pressure fluctuations consistent with a von Karman vortex street. The near and far wake regions, distinguished by the frequency content of the dominant pressure fluctuations, appear to be independent, implying that the von Karman vortex street does not substantially influence wing surface pressures.

Acknowledgments

This work was funded through NASA Ames Research Center Joint Research Consortium Agreement No. NCA2-786, with James Ross as project monitor.

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